Thrust Faulting, Block Rotation, and Large-Scale Mass Movements at Euboea Montes, Io

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Voyager stereo images of Io indicate that Euboea Montes formed when a large crustal block was uplifted 10.5 km above the volcanic plains and tilted ~6°. Uplift triggered a massive slope failure to the northwest, forming one of the largest debris aprons in the solar system. This slope failure probably involved relatively unconsolidated layers totalling ~2 km in thickness, overlying a rigid crust or lithosphere at least 11 km thick. We suggest that mountain formation on Io involves locallized crust-penetrating thrust faulting and block rotation, due to compression at depth induced during vertical recycling of Io's crust.

Jupiter's large moon Io is being volcanically resurfaced at such a high rate, estimated to be at least 1 cm/yr (1), that crustal recycling is probably occurring on a global scale. Although mountains cover only a few percent of the surface and have no obvious global pattern, understanding whether these mountains formed by volcanic, compressional, or extensional processes may indicate how Io's crust is being recycled. These mountains and the manner in which they collapse or are eroded are also potential indicators of crustal strength and composition. Vast featureless plains, which cover nearly half the surface and surround these mountains, present a different problem in that it is not known whether they formed by deposition of effusive lava flows, plume-derived ash, or other materials.

The discovery that Voyager obtained quality high-resolution stereo coverage of roughly 40% of Io in 1979 suitable for topographic mapping (2), together with Galileo's new observations of mountain distribution (3), has led to a reexamination of the morphology and origin of Io's mountains. Here, we report on new geologic and topographic observations of Euboea Montes (Fig. 1), a prominent mountain within Io's smooth plains. We examine two aspects of Euboea Montes: the geology and origin of the mountain and implications for crustal evolution, and geomorphic evidence for mass movement and implications for crustal stability and rheology.

The stereo images used for this work (Voyager images 16390.38 and 16392.59) have resolutions of 0.8 to 1.6 km/pixel, respectively, a stereo convergence angle of 49°, and a base-to-height ratio of 1.5. A digital elevation map (DEM) of Euboea Montes (Fig. 2) was generated using an automated stereogrammetry program, developed in 1995-1996 at the Lunar and Planetary Institute by Paul Schenk and Brian Fessler for use with Voyager images (2). The vertical precision of the Euboea Montes DEM is ~250 m. Formal errors associated with individual height measurements average 300 m.

Geology of Euboea Montes

Euboea Montes (47° S, 336° W) is a roughly oval-shaped massif 175 by 240 km across, surrounded by smooth nearly featureless plains on all sides. Within these plains are two low scarps 100 to 300 m high. These scarps face away from Euboea and are located 0 to 70 km from the eastern, southern, and western margins of the massif (Figs. 1, 2). They appear to be the eroded margins of layered deposits. There is widespread evidence for layering within Io's smooth plains, especially near the south pole (4). Scarp formation appears to involve the release of interstitial volatiles, which weaken the layers and make them susceptible to scarp retreat (5).

Euboea Montes itself can be divided into three geomorphic units. A NE-SW trending arcuate ridge crest or escarpment forms the spine of the massif. The highest elevation, 10.5 ±1 km above the plains, occurs along the center of this ridge crest, decreasing toward either end. This ridge crest divides Euboea into two sections. The southeast flank of the mountain is relatively steep and has a disrupted surface. The northwest flank forms a smooth planar surface sloping uniformly at ~6° to the northwest. Also, a 10 x 70 km wide block (plus one smaller block) has broken away from the southwestern end of Euboea Montes and moved intact roughly 3 to 4 km downslope.

Along the base of the planar northwest flank lies a thick ridged deposit with lobate margins. The ridges are a few km wide and up to 50 km long, and are oriented parallel to the downslope direction. In some cases, prominent ridges appear to form the margins or levees of individual lobes of this deposit. Along its upslope or proximal margin, the ridged deposit stands ~6 km above the plains, sloping gently and uniformly toward the distal toe. The toe of the deposit is roughly 3.5 km thick near the midpoint, decreasing to 2 km toward the northeast and southwest ends of the deposit, and the whole deposit is roughly 70 by 200 km across encompassing an area of ~14,800 km2.

Schaber (6) and Moore (7) suggested that the thick ridged deposit could be due to either viscous volcanic flow or slumping (perhaps due to creep induced by high heat flow (7)). Neither study reached any robust conclusions. Using the newly available stereo images and topographic data, we find that the morphology at Euboea is most consistent with slope failure along the entire face of the northwest flank, forming a massive debris apron at the base of the mountain. We observe no evidence for lava flows, vents, calderas, or any other volcanic features within the ridged unit. The lobes and longitudinal ridges on the apron resemble those observed in slope failures on other planets. Also, the width and thickness of the ridged deposit is directly correlated with the height and width of the exposed northwest flank of Euboea Montes. This correlation is not expected for volcanic deposits and indicates that a layer of roughly uniform thickness failed and moved off the flank of Euboea Montes to form this deposit, producing a greater accumulation of debris where the original surface was wider (i.e., the center of Euboea Montes).

Mass Movements on Euboea Montes

Two types of slope failure are observed at Euboea Montes. The first is the massive debris apron along the northwest flank described above. The morphological characteristics of this apron are similar to mass movement features on Earth, Mars and the Moon (8). Longitudinal ridges occur in deposits in different environments and with a diverse range of compositions. On Earth, they occur on debris aprons in dry volcanic materials (Aucanquilcha volcano, Chile (9)), non-volcanic materials (Blackhawk, CA (10)), ice (Altels, Austria (11)), and where there has been an ice or snow substrate (Sherman, AK (12)). Martian examples of aprons with longitudinal ridges include Mars 1 in Ganges Chasma (13) and on the Moon the deposit at Tsiolkovsky (14) has well defined ridges. Two possible origins have been proposed for the longitudinal ridges. They may indicate shear between substreams of debris travelling at different speeds or times. Alternatively, they could be the result of divergent motion of the debris (12).

These debris aprons are interpreted to be the product of rock and debris avalanches which are inertial granular flows (typically extremely rapid) derived from bedrock escarpments. The motion of the debris need not require an interstitial mixture for support, but can rely in large part (when dry) upon grain-to-grain interaction generating a matrix material through fracturing and grinding associated with the avalanche event (15). We use the term rock and debris avalanche to describe an inertial granular mass derived from parent rock that does not require an interstitial sediment-water mix or hot volcanic gases.

A minor break in slope within the debris apron on the northwest flank appears to be related to a plains scarp over which the material travelled. This scarp is a few hundred meters high and is one of the two that partially surround Euboea. The scarp stops where it intersects the toe of the debris apron but a trace of it appears to continue under it toward the east, where it ultimately reappears. This scarp, and the layer it forms the margin of, predates the formation of the debris apron. The parallel ridges that characterize the debris apron disappear at the location of this buried scarp, suggesting that the behavior of the moving material changed where the apron crossed the topographic scarp.

The volume of the massive debris apron on the northwest flank was estimated from the topography of the surface of the deposit. (The surfaces of the planar northwest flank of the mountain and the horizontal pre-collapse ground plane were extrapolated beneath the ridged deposit.) The estimated volume is ~25,000 km3, making it the largest debris apron known in the solar system, with the possible exception of the Olympus Mons aureole deposits on Mars (16). If this volume is restored as a uniform layer over the entire surface of the tilted northwest flank (its proposed pre-failure configuration), it would form a layer ~2 km thick. We propose that the two scarp-bounded 100-300 m thick layers surrounding Euboea were part of the original stratigraphic sequence prior to uplift, and were included in the material that formed the debris apron after uplift. If so, the estimated 2 km thickness of the debris apron material prior to failure may indicate the total thickness these layered deposits, at least in this region.

The formation of the debris apron at the base of a planar and uniformly sloping surface 200 km across indicates that movement at Euboea Montes occurred along a distinct planar discontinuity within Io's crust. The orientation of rock layering and discontinuities plays a major role in mass movement (17). The slides at Vaiont, Italy (18) and Sherman, AK (12) occurred along bedding surfaces. Movement of material on the northwest flank of Euboea may have been a result of a rheologic discontinuity between a weaker upper layer (which detached and travelled downslope) and a more competent lower crustal layer (which forms the Euboea massif); for example, a bedding contact between volcanic ash deposits and a mechanically stronger volcanic or thermally metamorphosed lower crustal layer. Alternatively, both upper and lower layers may have been competent and movement occurred along one or more distinct mechanical or stratigraphic discontinuities of unknown origin at ~2 km depth.

A large part of the toe of the debris apron was observed in a 250 m resolution image (Voyager FDS 16392.40). This surface has a homogeneous texture and appears to be free of blocks larger than ~500 m. This suggests that the material that formed the debris apron was poorly consolidated. This would tend to favor, although not require, the interpretation that the upper 2 km of crust forming the smooth plains are formed by relatively unconsolidated material such as volcanic plume-derived ash, or ash interbedded with lava flows.

The travel distance of the debris apron (from scarp crest to apron toe) is 130 km. Although this is a great distance compared with mass movements identified on Mars, Venus, or the Moon (19), submarine debris aprons on Earth have travelled distances in excess of 150 km and often travelled over very shallow slopes <5 degrees (20). The debris apron at Euboea follows the general correlation between greater descent height and greater run-out distance observed in avalanches on terrestrial planets (Fig. 3). Using Coulomb's law of sliding friction, an estimate of the coefficient of friction of a mass movement can be calculated by dividing the height from which material travelled (H) and the length over which is travelled (L). The ratio H/L equals the tangent of the slope angle of the line connecting the top of the scarp to the toe of the apron (9), and assumes frictionless motion on the slope. The H/L value for Euboea, which can be regarded as a mobility index for the debris apron, is 10.5/130 = 0.08, which overlaps with values for debris aprons on Venus, Mars, the Moon, and Earth (Fig. 3). Taking into account the variations in environmental conditions on the different planets such as gravity, atmospheric density, pressure and temperature, the distance that the Euboea apron travelled can be explained by the conversion of potential energy to kinetic energy. Essentially, the debris apron travelled as far as it did because of its large volume.

The second type of mass movement at Euboea Montes is represented by the large 10 x 70 km block (and the smaller adjacent block) that has detached from the southwestern end of the mountain and travelled 3 to 4 km down slope (Figure 1). These large blocks postdate the massive debris apron. They are similar to translational and possibly rotational failures and have analogs on the other terrestrial planets (21). The disrupted surface along the southeastern base of Euboea may consist of blocks that toppled and fell from the escarpment. The relatively smooth nature of these features indicates that failed material disintegrated during its transportation, possibly as a result of impact after free fall.

Origin of Euboea Montes

Slope failure at Euboea is limited to the formation of the debris apron, which probably involved movement of a thin relatively unconsolidated top layer, and the detachment of the two blocks at the southwest end. With these exceptions, the central Euboea Montes massif shows little deformation considering the amount of uplift (at least 10.5 km). This indicates that the uplifted and rotated block comprising Euboea represents an exposure of part of the lithosphere of Io, which must therefore be greater than 11 km thick (22), and has sufficient internal strength to maintain its shape over time. We model the shear stress at the base of the mountain due to its own weight at 10 to 13 MPa (assuming a density of 2500 kg/m3). This is well above the predicted shear strength of sulfur (23) and suggests that sulfur is not sufficiently abundant in the lower crust to weaken its rheology, consistent with arguments based on caldera depths (6, 21).

Other mountains on Io may also have been formed by block uplift and rotation. Haemus Montes (height 9 km) and an unnamed mountain 500 km west of Ra Patera (height 4 to 5 km (2)) are characterized by numerous parallel and inclined striations, and lack evidence of any volcanic features. Whether the striations on these mountains are due to the exposure of buried volcanic layers or to intense fracturing is unknown, but tectonic activity is strongly implicated in raising these mountains to heights of 5 and more km. Uplift and rotation of crustal blocks may thus be a common mechanism for mountain formation on Io.

The uplifted blocks comprising Euboea and probably other mountains on Io may be analogous to the basement-cored uplifts of the central Rocky Mtns. of Wyoming (24), and the Sierras Pampeanas in Argentina (25). These mountains formed during uplift of isolated oblong coherent basement blocks up to 150 km long. These blocks are bounded on one or more sides by steeply dipping (30 to 70°) thrust faults penetrating through most of the crust, and were covered by a relatively thin stratigraphic sequence prior to uplift. Like the ionian mountains, these upthrust basement blocks are surrounded by relatively undisturbed plains. This style of deep-rooted thrust faulting is usually termed “thick-skinned” deformation. Although this deformation involves vertical uplifts of 5 to 10 km, seismic profiles indicate that deformation is driven by regional compressional shortening of the crust (24, 26).

We propose that Euboea Montes and at least some of Io’s other mountains formed by a process similar to that which formed the basement-cored uplifts of the central Rocky Mtns. In this model, uplift and rotation of Euboea Montes occurred as a result of horizontal compression and crustal shortening along a deep-rooted thrust fault dipping steeply to the northwest beneath the massif. The thrust fault itself would be exposed along the southwest flank. The disrupted morphology of this flank could be due to slope failures or to fracturing along parasitic thrust faults that splayed off the main thrust fault, as is sometimes observed in the Rocky Mtns. (24).

The occurrence of thick-skinned deformation at Euboea and probably elsewhere on Io is consistent with a crust featuring a layered volcanic sequence only a few kilometers thick overlying a thick heterogenous basement. The basement is probably constructed of highly metamorphosed volcanic deposits and layers (formed by shield volcano and plains lava flows and by plume deposits) and multiple overlapping magmatic intrusions, both molten and solidified. These magmatic intrusions are related to the more than 170 volcanic craters observed on Io (6).

Based on these observations and analogies, a simple scenario for the origin of mountain building on Io is suggested. Recent Galileo observations (27) suggest that over time volcanism, or at least volcanic hotspot distribution, occurs roughly uniformly over the surface. In a global context, this implies that as new volcanic layers and deposits are formed on the surface, older layers are forced to subside more or less uniformly into the interior. As this occurs, the effective radii of these spherically concentric shells decrease, throwing the lower crust or lithosphere into compression. This global compressional stress is relieved in quasi-random locations by crust-penetrating thrust faulting and uplift of large crustal blocks. Specific occurrences of failure may be triggered by anisotropies in the crust, as is the case in the Rocky Mtns. (24), or by locallized weakening of the crust by volcanic intrusions or vents, such as Creidne Patera, an 80 by 170 km wide caldera located only 40 km southeast of Euboea. A caldera is also located adjacent to Haemus Montes, a prominent mountain near the south pole.

In the case of Euboea Montes, uplift was followed by slope failure of at least two types; translational movement of material along a planar discontinuity, plus rotation and slumping of coherent blocks 10's of km across. The translational movement along the northwest flank formed a massive debris apron larger than any thus far recognized in the solar system (with the possible exception of disrupted terrain near Olympus Mons), and exposed part of the stratigraphy of Io's crust. The material that failed involved an upper crustal layer ~2 km thick that was apparently relatively unconsolidated and extensive over large areas of Io's surface. This layer may have been composed of volcanic ash deposits or ash interbedded with volcanic flows. Beneath this upper layer is a coherent crust or lithosphere at least 11 km thick.

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FIGURES

Figure 1. Stereo pair of Euboea Montes from Voyager 1.

Figure 2. Color coded topographic map of Euboea Montes.

Figure 3. Mobility index (H/L) and volume of debris aprons on terrestrial planets and Io.

Possible Cover Image. Perspective view of Euboea Montes.